New DAQ for the HJET polarimeter at RHIC

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The RHIC/AGS Polarimetry Group:
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H-Jet polarimeter: (96 channels)
- measure average (absolute) polarization of RHIC beams
The HJET polarimeter was commissioned in 2004. It was designed to measure absolute polarization of 24-250 GeV/c proton beams with systematic errors better than ∆P/P ≤ 0.05. The atomic hydrogen polarization in the Jet is about 96%. The Jet polarization is flipped every 5 min.

New in Run 2015:
- 500 μm Hamamatsu detectors
- DAQ based on VME 250 MHz 12 bit FADC250 (JLab) wave form digitizers.
Beam Polarization Measurement in HJET

In elastic pp scattering, the asymmetry of low energy ($T_R < 10$ MeV, 90°) recoil protons is measured.

\[ a = \frac{N_L - N_R}{N_L + N_R} = \frac{N^\uparrow - N^\downarrow}{N^\uparrow + N^\downarrow} = A_N(t) P \]

For left/right symmetric detectors and spin flipping measurements, the systematic errors may be strongly suppressed

\[ a = \sqrt{\frac{N_L^\uparrow N_R^\downarrow - N_R^\uparrow N_L^\downarrow}{N_L^\uparrow N_R^\uparrow + N_R^\uparrow N_L^\downarrow}} \]

Both, beam and jet asymmetries are measured simultaneously

\[ a_{beam} = A_N(t) P_{beam} \quad a_{jet} = A_N(t) P_{jet} \]

\[ P_{beam} = \frac{a_{beam}}{a_{jet}} P_{jet} \]

Both RHIC beams (Blue and Yellow) are measured simultaneously

\[ t = (p_{out} - p_{in})^2 = -2m_p T_R \]

\[ \frac{z - z_{jet}}{L} \approx \theta_R \approx \sqrt{\frac{T_R}{2m_p} \frac{E_{beam} + m_p}{E_{beam} - m_p}} \]

Analyzing power:

\[ A_N(t) \sim 0.04 \]

31 GeV: Preliminary
100 GeV: PLB 638 (2006) 450
250 GeV: Preliminary
New Silicon Detectors
(Hamamatsu Photonics K.K. S10938-3627)

**Four detectors on one side:**

- Detector size: $45 \times 45 \text{ mm}^2$
- Gap between detectors: $\approx 19 \text{ mm}$
- Strip size: $3.7 \times 45 \text{ mm}^2$
- Gap between strips: $50 \mu\text{m}$
- Depletion region: $470 \mu\text{m}$
- Uniform Dead-layer: $\sim 0.37 \text{ mg/cm}^2$
- Distance to the beam: $770 \text{ mm}$
- Bias Voltage: $150 \text{ V}$

- **The detector geometry allows to detect recoil protons (elastic $pp$) with kinetic energy up to 11 MeV.**
- **Protons with energy above 7.8 MeV punch through the detector (only part of kinetic energy is detected).**
- **An ability to proper reconstruction of the punch through protons was an important requirement for the new DAQ.**
Old CAMAC based DAQ (2004-2015)

- 2 CAMAC Crates (USB connection to PC)
- 24 WFD Boards (Yale University)
  - 4 channels per board
  - 8 bit
  - 140 MHz (effectively 420 MHz)
  - Custom Firmware (deadtime-less)
  - External signals:
    - Clocks derived from 28.15 MHz RF signal
    - Bunch Zero (every beam rotation)
    - Veto
    - Delimeter
- External signal (Jet polarization status)
- CAMAC I/O registers and NIM electronics

Signal Amplitude and Time:

$\Delta t = \frac{A_{\text{max}}/2}{dA/dt} = t_{1/2} - t_{\text{meas}}$

The DAQ was used in the first part of the RHIC Run15.
New VME based DAQ (2015-...)

- Wiener VME 64x crate + Single Board Computer
- 6 FADC Boards (Jefferson Lab)
  - 16 channels per board
  - 12 bit
  - 250 MHz
  - General Purp. Firmware
    - internal trigger
    - deadtime-less
    - raw waveform available
  - External signals:
    - 244 MHz Clocks derived from 28.15 MHz RF signal
    - Sync Reset (every Jet Cycle, ~5 min)

- Front Panel Signal Distribution Module (Jefferson Lab)
- BNL V128 Input-register (Jet polarization status)

Total Rate in HJET ~ 10 kHz (2 Mbyte/s) allows us to use FADC general purpose firmware and acquire raw waveforms (80 samples -> 328 ns)

- The new DAQ was assembled without destroying the old DAQ. The infrastructure of the old DAQ was employed in the new one.
- It takes only about 30 min. to switch between DAQ’s (reconnection of 96 signal cables)
- A software interface to use new data format with old analysis was developed.
- This allows us to migrate to new DAQ smoothly.
- New data analysis was also developed.

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Single Board Computer (SBC)

- 4-core 2.1 GHz Intel Core i7-3612QE Processor
- 16 Gbytes DDR3-1600 DRAM with ECC
- VME64 interface supporting A64/A32/A24/A16/D64/D32/D16/D8(E0), MBLT64, 2eSST and 2eVME
- 500 Gbyte Hard Drive
- Red Hat Enterprise 6 Linux

The SBC is powerful enough to provide detailed online analysis in parallel with data taking.
**FADC250**

**VME64x Flash ADC Module Specifications**

<table>
<thead>
<tr>
<th>Signal Inputs</th>
<th>Number</th>
<th>16 S Version (50 Ohm, LEMO)*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Range</td>
<td>-0.5V, -1V &amp; -2V, User Selectable</td>
<td></td>
</tr>
<tr>
<td>Offset</td>
<td>±10% FS per channel via DACs</td>
<td></td>
</tr>
</tbody>
</table>

**Clock**

| Sampling      | 250 MSPS, Differential |
| Jitter        | 1 pS (10-bit ADC), 350 fs (12-bit ADC) |
| Source        | Internal and External |

**Control**

| Clock          | IN – Diff., LVPECL (Front Panel & Backplane) |
| Status 1       | OUT – Differential (Front Panel & Backplane) |
| Status 2       | OUT – Differential (Front Panel & Backplane) |
| Sync           | OUT – Differential (Front Panel & Backplane) |
| Trigger SW     | Software Strobe (Internal) |

**Conversion**

| Resolution     | 10-bit (8 and 12-bit by chip replacement) |
| DNL            | ± 0.8 LSB |
| DNL            | ± 0.5 LSB |
| SNR            | 56.8 dB @ 100 MHz Input |
| Data Latency   | 32 nS |

**Trigger Latency**

| 8 µS |

**Data Memory**

| 8 µS |

**Data Processing Specification**

- Windowing
- Charge, Pedestal, Peak
- Time (Over Threshold, Relative to trigger)
- Output (Backplane, VXS)

**Interface**

| VME64x – 2eVME Data Transfer Cycles (40, 80, 160 & 320 MB/sec) with VXS-P0 |

**Packaging**

| 6U VME64x |

**Power**

| +3.3V, +5V, +12V, -12V |

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**The board was designed for the Jlab Hall D.**

- **16 Channel**
- **12 bit, 250 MHz**
- **Internal Trigger, deadtime free**
- **Waveform length up to 511 samples (2 µs)**
- **Dead Time Free**

**External Inputs:**

(from the Signal Distribution Card)

- **Trigger**
- **Sync Reset**
- **Clocks**

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[Image of the board and a penny for scale]
Front Panel Signal Distribution Module for the FADC250 (FP-SD)

The board was designed for the Jlab Hall D.

- The SD-FP distributes synchronized Clock, Trigger, and Sync Reset signals to up to 7 FADC250 boards.
- Supports external and internally generated signals

For RHIC Run15 we borrowed 7 FADC 250 boards and FP-SD from JLab.

We have got significant help from Jlab Fast Electronics Group. FADC Firmware was upgraded in accordance with our requirements.

We acknowledge the outstanding contribution of Chris Cuevas, Hai Dong, Ed Jastrzembski, and Bryan Moffit to the development the new DAQ for the Hjet polarimeter at RHIC.
Waveform Processing

Two processing methods were implemented

1. The same as for CAMAC DAQ (finding maximum amplitude and rising edge slope)
2. Waveform Fit

Signal parametrization:
\[ W(t) = p + A (t - t_i)^n \exp\left(\frac{t - t_i}{\tau_s}\right) \]

\[ t_m = t_i + n\tau_s \]

To isolate recoil proton the time of flight energy is compared with energy deposited in detector:

\[ E_{\text{kin}} = \frac{M_p L^2}{2(t - t_0)^2} = \alpha A + E_{\text{loss}}(A, x_{DL}) \]

Parameters \( \alpha, t_0, \) and \( x_{DL} \) are determined in the calibration.
Calibration Using Alpha-sources

All Si detectors are exposed by 2 α-sources: 
- $^{148}\text{Gd}$ (3.183 MeV)
- $^{241}\text{Am}$ (5.486 MeV)

Gain ($\alpha \sim 2.5$ keV/cnt) and dead-layer thickness ($x_{DL} \sim 0.37$ mg/cm$^2$) were measured for every Si strip.

Energy resolution $\sigma_E \approx 20$ keV is dominated by electronic noise. (For CAMAC DAQ $\sigma_E \sim 30$ keV)
**Good Event Isolation**

### Elastic pp:

\[ p + p \rightarrow p + p \]

\[ z \approx L \frac{r}{2m_p} \]

### Non-elastic pp:

\[ p + p \rightarrow p + p + \pi \]

\[ z \geq L \sqrt{\frac{T}{2m_p}} \left(1 + \frac{m_p m_{\pi}}{E_{beam T}}\right) \]

### Background:

\[ p + A \rightarrow p(\alpha, \ldots) + X \]

Same signals in all strips

### Beam Halo:

\(~1.5\ MeV\ signals\ produced\ by\ beam\ halo\ MIP’s.\ Correlated\ with\ beam\ buckets.\)

Same signals in all strips

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Simulation (arbitrary normalization)

- Elastic pp
- Non-elastic pp

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14 Sep 2015

PSTP 2015, Ruhr-Universitat Bochum
Elastic events selection cuts are on based on $t - t_p(E)$ and $\sqrt{E} - \sqrt{T_{\text{strip}}}$ cuts, where $t$ and $E$ are measured time and energy, $t_p(E)$ is proton time corresponding energy $E$, and $T_{\text{strip}}$ is proton kinetic energy corresponding considered Si strip.
Geometry Based Calibration

For elastic $pp$ only scattering, the recoil proton distribution on $\sqrt{A}$ may be considered as an image of jet / beam gas z-coordinate profile (smeared by strip width), because $\sqrt{A} \propto \sqrt{T} \propto (z_{\text{strip}} - z_{\text{jet}})$

$$\sqrt{A_{\text{max}}} \iff \sqrt{T_{\text{strip}}} = \sqrt{\frac{2m_p}{E_{\text{beam}} + m_p} \frac{E_{\text{beam}} - m_p z_{\text{strip}}}{L}}$$

This is a calibration equivalent to the calibration with $\alpha$- source.

In real world, $T_{\text{strip}} = T_{\text{strip}}(z_{\text{strip}}, p_i)$, Where $p_i$ are corrections including z-coordinate misalignments of eight Si detectors, magnetic field corrections for left and right side. In turn, corrections $p_i$ depend on beam angle and x-coordinate.

Corrections $p_i$ have to be determined before geometry based calibration can be used.
For every acceptable strip we can compare elastic peak time $t_{\text{max}}$ and prompt time $t_{\text{prompt}}$. The prompt time of flight time $t_{\text{TOF}}$ is assumed to be the same for all strips.

Correction parameters and prompt time of flight may be found by minimizing

$$\chi^2 = \sum_{\text{strips}} (t_{\text{prompt}} - t_0(p_i) - t_{\text{TOF}})^2$$

where

$$t_0(A_{\text{max}}, p_i) = t_{\text{max}} - \frac{L}{c} \frac{2T_{\text{strip}}(p_i)}{m_p}$$

Control for the Beam / Detector Geometry

For $|A - 20| < 3$

$\chi^2 = \sum_{\text{strips}} (t_{\text{prompt}} - t_0(p_i) - t_{\text{TOF}})^2$

where

$t_0(A_{\text{max}}, p_i) = t_{\text{max}} - \frac{L}{c} \frac{2T_{\text{strip}}(p_i)}{m_p}$

$|A - A_{\text{max}}| < 3$

$t_{\text{prompt}} = t_0 + t_{\text{TOF}}$

$t_{\text{max}} = t_0 + \frac{L}{c} \frac{2T_{\text{strip}}(p_i)}{m_p}$
Time Alignment

- For each Si strip time offset $t_0$ can be determined with accuracy better $120\,\text{ps}$ from prompt time measurements.
- Some systematic dependence of measured time on amplitude is observed. Proper accounting of these dependence will improve accuracy of time alignment.
- The positions of all detectors may be reconstructed with accuracy $\sim 100\,\mu\text{m}$.
- Variations of magnetic field and beam direction and x-coordinate may be monitored with accuracy equivalent to $\sim 100\,\mu\text{m}$.

For CAMAC DAQ $\sigma \approx 300\,\text{ps}$
Comparison of geometry based and alpha-calibrations.

The geometry based and alpha calibrations are absolutely independent, but they may be directly compared.

\[ \Delta E = T_{\text{strip}} - E_{\text{cal}}(A_{\text{max}}, \alpha, x_{\text{DL}}) \]

For proton energy range 1-6 MeV the calibrations were found to be consistent within 0.5% precision.

Systematic errors in energy calibration
\[ (\sigma_{E/E})_{\text{syst}} < 0.5\% \quad (< 0.25\% ?) \]

8-hour run followed immediately after alpha-calibration run was used for geometry based calibration. In 24 hours the consistency of two calibrations were degraded to 0.7%.

For CAMAC DAQ \( \sigma \approx 1.5\% \)

\[ \delta = \Delta E / \langle E \rangle \]

\[ \delta(A) = (0.02 \pm 0.08) + (-0.16 \pm 0.24)A^{75.100\%} \]

Amplitude [WFD units]

\[ \text{Mean} = 0.02\% \]
\[ \text{RMS} = 0.51\% \]

\[ \sigma \approx 0.5\% \]
**Event distributions for stopped protons**

- Background near the signal peak. Evaluation under background is needed.
- Well isolated elastic signal with “right” (gaussian) shape.
Above 5 MeV stopped and punched through proton signals are strongly overlapped in time – amplitude distributions.
The distributions are for Si1 (the strip with elastic punched through protons).

$n^{(\alpha)}$ and $\tau^{(\alpha)}$ are waveform fit parameters determined in alpha calibration.

The waveform shape is stable for proton energies up to 6 MeV. Then, it changes significantly.

Fluctuations of $n$ and $\tau_s$ in the fit are strongly correlated:
1. We should account the correlation
2. We can fix $\tau$ to $\tau^{(\alpha)}$

We need not only describe the dependence $n = n(A)$, but also properly parameterize it:
$n = n(E_{kin})$ and $A = A(E_{kin})$
Signal Simulation

Ionization losses:

\[ E_{\text{bias}} = M_{\text{bias}} + M_{\text{dep}} \]

\[ E_{\text{min}} = \frac{d}{v_{e,h}(x)} = \mu_{e,h} E(x) \]

\[ S(t) \sim |v_e(t)| + |v_h(t)| \]

Charge Collection:

\[ A(t) \propto \int S(\tilde{t})(t - \tilde{t})^n e^{-\frac{(t-\tilde{t})}{\tau}} d\tilde{t} \Rightarrow A_i \]

The depletion voltage \( V_{\text{dep}} = 125 \text{ V} \) was selected for the best fit of the data.

Proton Energy

- 2.5 MeV
- 5.0 MeV
- 7.5 MeV
- 10.0 MeV

\( 241\text{Am} \) signal was simulated to parameterize digitization.
Predictions for waveform parameters dependence on proton kinetic Energy

Nonlinearity for energies just below the punch-through threshold

\[ \Delta t \] is variation of measured time caused by waveform shape dependence on kinetic energy (actually, the systematic error in measurements). The offset was arbitrarily chosen as

\[ \Delta t(E_{kin} = 5.486 \text{ MeV}) = 0 \]
Event selection

The consistency between simulation and experimental data is not perfect, but sufficiently good for preliminary analysis.

- Event selection cuts are not optimized yet.
- More work is still needed for routine parametrization $n = n(A)$ for all Si strips.
Waveform shape cuts applied. **Stopped protons.**

The background was strongly suppressed.
Waveform shape cuts applied. **Punched through protons.**

The time bias gone.

Nonlinearity was strongly suppressed.
The proton energy range can be extended to **0.5 – 10.5 MeV**
- **0.5 MeV** is defined by internal trigger threshold in FADC
- **10.5 MeV** is defined by geometrical acceptance of Si detectors

- Background is substantially suppressed for low energy (stopped) protons.
- In the pictures, background is actually counted 12 times, in reality background is smaller.
Systematic Errors in the H-Jet Measurements

\[ P_{beam} = P_{jet} \times (a_{beam}/a_{jet}) \]

Jet Polarization: there are 2 hydrogen components in the jet:
- atomic with (measured) polarization \( P_{BR} \approx 96\% \)
- molecular (unpolarized)

The admixture of molecular hydrogen was measured to be \( \epsilon \approx 3\% \) but, but systematic errors of this measurement is not well known. The average polarization
\[ P_{jet} = (1 - \epsilon) \times P_{BR} \]
should be used in analysis.

Background:
\[ A_N^{\text{eff}} = \frac{A_N + rA_N^{\text{bgr}}}{1 + r} = A_N \frac{1 + \alpha r}{1 + r}; \quad \alpha = A_N^{\text{bgr}} / A_N \]

\( r \sim 5\% \) is background level
For Jet asymmetry \( \alpha = 0 \).
For beam asymmetry \( \alpha \) is unknown and may be as large as 1 (e.g. for beam gas protons and molecular hydrogen).

\[ P_{meas} = P_{beam} (1 + \alpha r) \]

(some previous experimental estimates gave \( \alpha \approx 0 \))
The main signal distributions used to isolate elastic pp events have small and flat background. We can try to subtract it. It should be done separately for all 4 Jet/Beam polarizations.

Even more promising is subtraction of average (over detector) background. In this case background may be properly subtracted. Probably, such a subtraction should be done separately for Blue/Yellow and Left/Right detectors.

We may expect that molecular hydrogen component will also be subtracted.

The method, as described, was not implemented yet.
**Fast estimation of background related systematic errors.**

**A conservative (??) estimate for background related systematic errors is \( \delta P / P \leq 1\% \)**

Molecular hydrogen background is supposed to be accounted.

The \( p\bar{p} \rightarrow p\bar{p}\pi \) background requires special consideration.

A study of “systematic errors in evaluation of systematic errors” has to be done.

- Linear dependences on \( \Delta \) !
- Extrapolation to \( \Delta = 0 \) will give background (systematic error ?) free result.
- The corrections to \( A_N \) and \( P_{\text{beam}} \) are shown on plots. (statistical error only)

**Variation of the cut parameter \( \Delta \) will result in proportional variation of background contribution but only in a small change of the signal contribution**
Summary

• New DAQ based on VME 12 bit 250 MHz FADC250 for RHIC Hjet polarimeter was assembled, tested, and employed in RHIC Run 2015
• Different calibration methods were tested
  ✓ Energy resolution ~ 20 keV
  ✓ Systematic errors in energy calibration $\delta E/E < 0.5\%$ for 1-6 MeV protons
  ✓ Time alignment of electronic channels is better than $\delta t < 120$ ps
  ✓ z-coordinates of detectors may be monitored with accuracy $\delta z \sim 100 \mu m$
  ✓ beam angle and x-coordinate may be monitored with accuracy 0.1 mrad and 100 $\mu m$, respectively.
• A method of full reconstruction of punched through protons was developed
  ✓ Recoil proton energy range was increased to 0.5 – 10.5 MeV
  ✓ Background for stopped protons was suppressed
• Preliminary study of systematic errors in polarization measurement was performed.

• All presented results were obtained with RHIC Fill 18950-19953 data
• Further adjustment of event selection cuts is still needed.
• Adopting the developed methods for the CAMAC data is forthcoming.